Physics with charmonia at SPD

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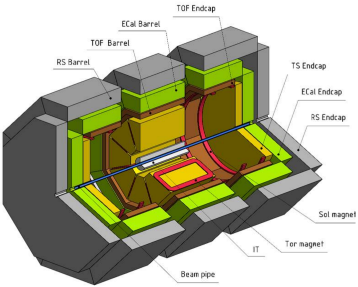
SPD



Possible SPD set-up

SPD: physics with polarized hadron beams at $10\text{ GeV} < \sqrt{s} < 26\text{ GeV}$

Spin-dependent hadron structure can be probed with

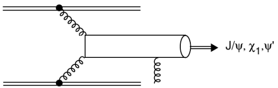
- Drell-Yan process,
- **charmonia production,**
- prompt photons,
- ...

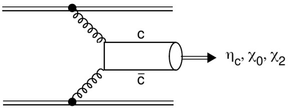
For charmonia production SPD will have the following advantages:

- high statistics,
- good momentum resolution,
- open geometry and ability to detect χ_c states.

J/ψ production in hadronic collisions

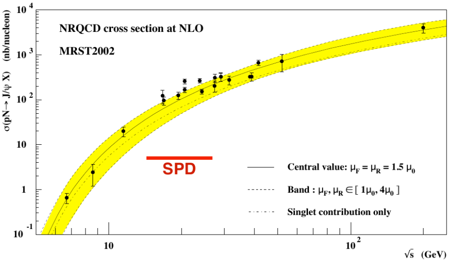
- J/ψ (and charmonia) production:
  - is sensitive to gluon and quark PDFs,
  - has large cross-section and very distinct signal in the dimuon mode,
  - is theoretically ambiguous,
  - is complicated due to the presence of feed-down contributions.
- Complementary to the **DY** (for quark PDFs) and **prompt photons** (for gluon PDF) programs.
- Study and verification of J/ψ production mechanisms would be crucial to interpret measured J/ψ spin asymmetries or angular modulations and to extract the gluon PDF of mesons in future experiments at similar c.m.s. energies (e.g. AMBER).





Diagrams from
Int.J.Mod.Phys.A10:3043-3070,1995

J/ψ production at SPD



SPD experiment

- 4π coverage
- open spectrometer
- good momentum resolution
- high statistics (20M J/ψ are expected to be produced at SPD per year [SPD LOI])

- ability to study also ψ' and χ_{cJ} states (cross-section, p_T and x_F spectra, polarization)
- J/ψ production is suggested to probe the Sivers effect for gluons in pp collisions (PRD96 036011 (2017), Boer 2017)) and quark spin asymmetries in $\bar{p}p$ collisions (Phys.Lett.B594(2004)97, hep-ph/0604176).

what can be measured.

Feed-down contributions

HERA-B, Phys.Rev.D79:012001,2009

- $\chi_{cJ} \to \gamma J/\psi$: $\approx$ 30%

Exp.	beam/ target	$\sqrt(s)$ GeV	$N_{J/\psi}$	N_{χ_c}	$R\chi_c$	$\frac{\sigma(\chi_{c1})}{\sigma(\chi_{c2})}$	$\sigma(\chi_{c1})$ (nb/n)	$\sigma(\chi_{c2})$ (nb/n)
ISR [6]	pp	$< 55 >$	658	31 ± 11	0.43 ± 0.21			
R702 [7]	pp	52.4,62.7	975		$0.15^{+0.10}_{-0.15}$			
ISR [8]	pp	62			0.47(8)			
E610 [9]	pBe	19.4,21.7	157 ± 17	11.8 ± 5.4	0.47(23)	0.24(28)	39(49)	162(81)
E705 [10]	pLi	23.8	6090 ± 90	250 ± 35	0.30(4)	0.09(29)(17)	24(48)(2)	244(83)(16)
E771 [12]	pSi	38.8	11660 ± 139	66	0.76(29)(16)	0.61(24)(4)	488(128)(56)	805(231)(92)
HERA-B [14]	pC,Ti	41.6	4420 ± 100	370 ± 74	0.32(6)(4)			
CDF [11],[13]	$p\bar{p}$	1800	$\{^{88000}_{32642 \pm 185}$	$\{^{119 \pm 14}_{1230 \pm 72}$	0.297(17)(57)	1.19(33)(14)		

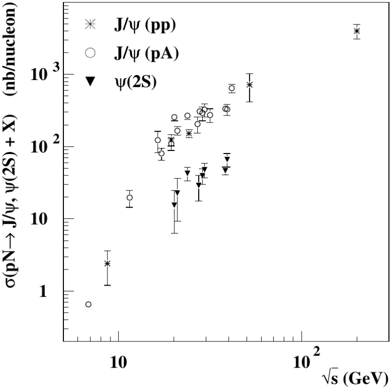
- $R_{12} = \frac{\sigma(\chi_{c1}) B(\sigma(\chi_{c1}) \to \gamma J \psi)}{\sigma(\chi_{c2}) B(\sigma(\chi_{c2}) \to \gamma J \psi)}$

	R_{12}
C	$1.06 \pm 0.21_{st} \pm 0.37_{sys}$
Ti	$0.67 \pm 0.67_{st} \pm 0.23_{sys}$
W	$0.98 \pm 0.36_{st} \pm 0.34_{sys}$
Tot	$1.02 \pm 0.17_{st} \pm 0.36_{sys}$

- $\psi' \to J/\psi X$: $\approx$ 10%
- In total feed-down contributions account for $\approx$ 40% of the inclusive cross-section.

ψ' production

The ψ' production in fixed-target experiments and low energy *pp* collisions. The cross-section for nuclear target is $\sigma_{\psi'}^{pA} = \sigma_{J/\psi'} \cdot A^{\alpha}$, where $\alpha = 0.96$.



Experiment	Reaction	$\sqrt{s}$ (GeV)	$\sigma_{\psi(2S)}$ (nb/nucleon)	$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ (R_ψ)
E331 [28]	pC	20.6	15.4 ± 9.1	0.060 ± 0.035
E444 [29]	pC	20.6	22.8 ± 13.5	0.137 ± 0.079
E705 [31]	pLi	23.8	42.5 ± 9.0	0.159 ± 0.029
E288 [33]	pBe	27.4	28.9 ± 11.3	0.141 ± 0.042
NA38/51 [35, 36]	pA	29.1	39.3 ± 9.6	0.135 ± 0.015
NA50 [37]	pA	29.1	47.1 ± 10.9	0.145 ± 0.017
E771 [41]	pSi	38.8	46.3 ± 5.7	0.139 ± 0.020
E789 [42]	pAu	38.8	66.1 ± 14.1	0.202 ± 0.055

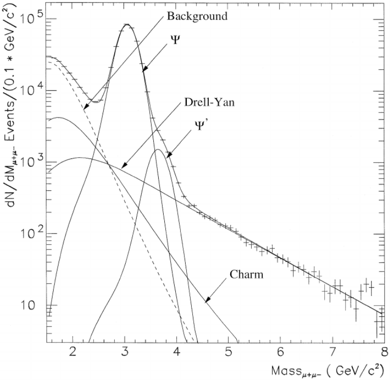
- ψ' production cross-section is by ≈ 0.15 lower than for J/ψ;
- $Br(\psi' \to \mu^+\mu^-) \approx 0.1 \times Br(J/\psi \to \mu^+\mu^-)$;
- The ψ' statistics is expected to worser by factor of 60, but there are no feed-down contributions!
- At SPD the $J/\psi\pi^+\pi^-$ mode can be also used to reconstruct ψ'!

Figure and table from Phys.Lett.B638:202-208,2006.

ψ' production

The ψ' production in fixed-target experiments and low energy *pp* collisions. The cross-section for nuclear target is $\sigma^{pA}_{\psi'} = \sigma_{J/\psi'} \cdot A^{\alpha}$, where $\alpha = 0.96$.

NA51



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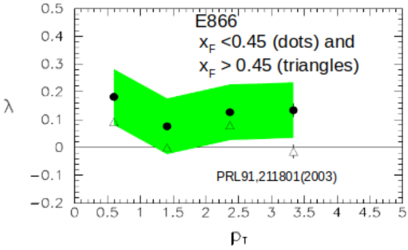
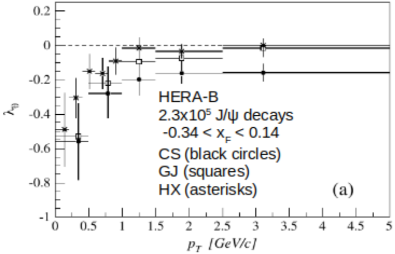
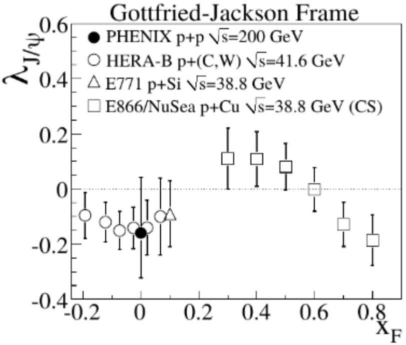
J/ψ polarization at low energy pp and pN collisions

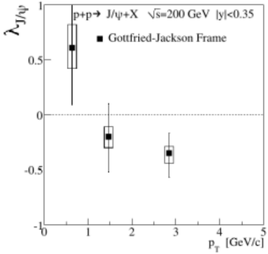




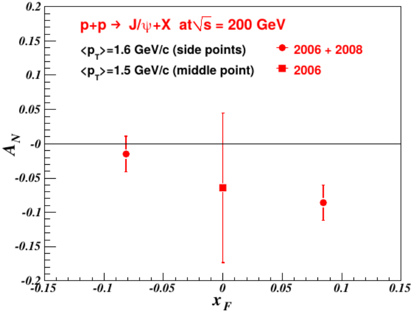
EPJC 60,517 (2009)



PRD82,012001(2010)



TSSA in J/ψ production at PHENIX

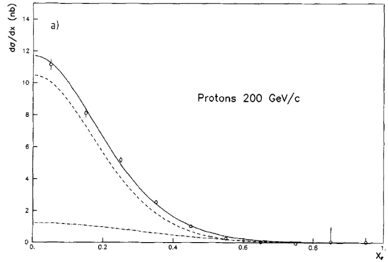


PRD 82, 112008 (2010)

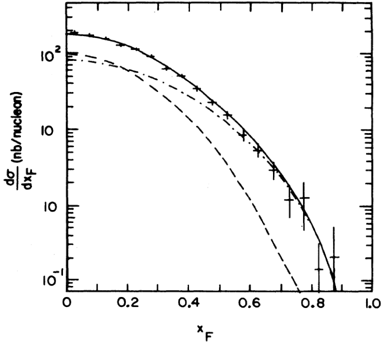
- asymmetry at forward x_F measured with statistical significance of 3.3σ
- approximately 22,000 J/ψ events analyzed
- 2σ indications for nonzero asymmetry were also reported in PRD98, 012006 (2018)

One separation of quark-antiquark annihilation and gluon fusion in the past

Hard part of $d\sigma/dx_F$ for pp ($\sqrt{s} = 19$ GeV) fitted by NA3 (Z.Phys.C 20,101(1983)). Dashed line is gluon fusion and dot-dashed is $q\bar{q}$ annihilation.



$d\sigma/dx_F$ for $\bar{p}W$ ($\sqrt{s} = 15$ GeV) fitted by E537 (PRD 48 5067 (1993)). Dashed line is gluon fusion and dot-dashed is $q\bar{q}$ annihilation.



Current approaches to quarkonia production

- Color evaporation model (CEM)
- Non-relativistic QCD (NRQCD)

Color evaporation model

Phys.Rev.C61:035203,2000

- Inclusive ($A + B \to J/\psi + X$) production is proportional to cross-section of $c\bar{c}$ production below open charm threshold (e.g. see PRC 61 035203).

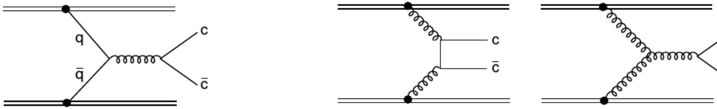
$$\frac{d\sigma_H^{AB}}{dx_F} = F_H \int_{4m_c^2}^{4m_D^2} \frac{dm^2}{\sqrt{x_F^2 s^2 + 4m^2 s}} H_{AB}(x_1, x_2, m^2),$$

where

$$H_{AB}(x_1, x_2, m^2) = f_g^A(x_1) f_g^B(x_2) \cdot \hat{\sigma}_{gg}(m^2) + \sum_{q=u,d,s} \left[f_q^A(x_1) f_{\bar{q}}^B(x_2) + f_{\bar{q}}^A(x_1) f_q^B(x_2) \right] \hat{\sigma}_{q\bar{q}}(m^2),$$

$$x_{1,2} = \frac{1}{2} \left(\pm x_F + \sqrt{x_F^2 + 4m^2/s} \right).$$

- F_H are assumed to be process independent.
- LO $c\bar{c}$ production diagram (calculations beyond LO are also available):

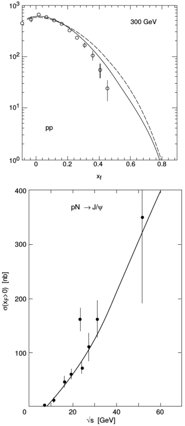


(diagrams from Int.J.Mod.Phys.A10(1995) 3043)

Color Evaporation Model

- **Sum over colors and spins of $c\bar{c}$ pair is assumed** (emission of one or more soft gluons is assumed to neutralize color). **No predictions on charmonia polarization.**
- Relative contributions from $q\bar{q}$ annihilation and gg fusion is given by parton cross-sections and can be validated with x_F distribution.
- CEM predicts $\sqrt{s}$-dependence.
- The p_T can be approximately reproduced with NLO and random k_T-smearing for Tevatron energies.
- Process independence of F_H factors holds only approximately (Phys.Rev. D72 (2005) 014004).
- In PRD85, 094013 (2012) used to estimate TSSA for photoproduction of J/ψ.

Data from E705 Collaboration



Figures from Int.J.Mod.Phys.A10(1995) 3043

NRQCD

Phys.Rev.D54:2005,1996

For the process $A + B \to H + X$ in the collinear factorization:

$$\sigma_H = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1) f_{i/B}(x_2) \hat{\sigma}(ij \to H).$$

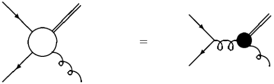
1. **Conjecture** of the cross-section factorization to short-distance ($x \approx 1/m_c$) and long-distance parts:

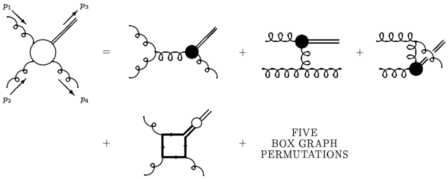
   $$\hat{\sigma}(ij \to H) = \sum_n C^{ij}_{Q\bar{Q}[n]} \langle O^H_n \rangle.$$

   $C^{ij}_{Q\bar{Q}[n]}$ (SDC) describe heavy quark pair production, $\langle O^H_n \rangle$ long distance matrix elements (LDME) describe its hadronization to quarkonium H and $n =^{2S+1} L^{(1,8)}_J$. **Proven only for sufficiently large p_T.**
2. **Hierarchy** of LDME $\langle O^H_n \rangle$ with respect to v ($v^2 \approx 0.2-0.3$ for charmonium).

Expression for cross-section is a **double** series in α_s and v. There are indications that the series is well-converged.

- Example 1: LO same as shown for the CEM model.
- Example 2: diagrams (NLO process) which mediate $q\bar{q} \to J/\psi g$, $qg \to J/\psi q$ and $gg \to J/\psi g$ through $c\bar{c}(^3P_J^{(8)})$ $c\bar{c}(^1S_0^{(8)})$ (*from Phys.Rev. D53 (1996) 6203-6217):*





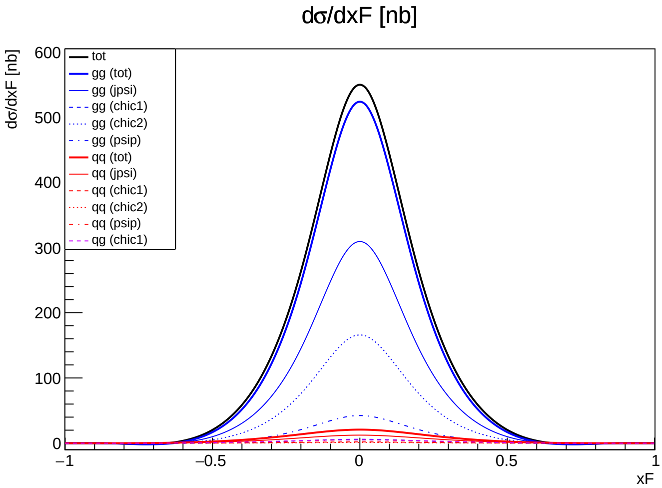
Ingredients:

- **SDC** are determined from NRQCD.
- The **singlet LDME** are determined from charmonium decays or charmonium wave function in potential models ($O(v^2)$).
- The **octet LDME** are determined from the fits to experimental data.
- The are **lattice** calculations only for $\langle O_1^{\chi_{cJ}}(^3P_J)\rangle$ and $\langle O_8^{\chi_{cJ}}(^3S_1)\rangle$ (Phys.Rev.Lett.77(1996)2376). They are reasonably consistent with global fits (Braaten, Lectures on NRQCD factorization).

Predictions:

- x_F, sensitive to relative contributions from quark-antiquark annihilation and gluon-gluon fusion;
- p_T in for $p_T > 2m_c$ for collinear factorization (not at SPD energies);
- charmonia polarization;
- $\sqrt{s}$ dependence.

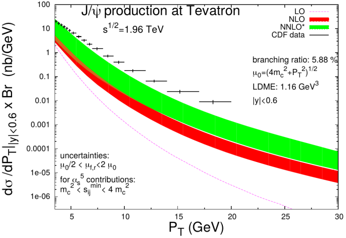
$d\sigma/dx_F$: contribution of subprocesses



- pp at $\sqrt{s} = 26$ GeV
- Formulas and LDME from Phys.Rev.D54:2005,1996
- PDF: NNPDF23 NLO

- **LO NRQCD fits**: **severe inconsistency** in LDME (Tevatron data + cross-section of the fixed target experiments (Beneke and Rothstein, 2005)), unable to described J/ψ polarization.
- **NLO corrections are significant** (here as function of p_T):

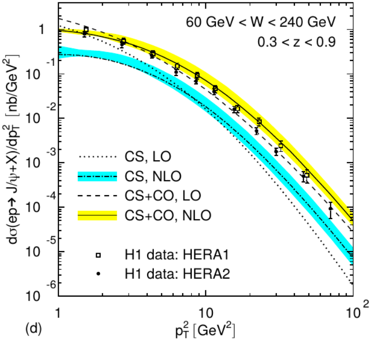
Color singlet:



Plot by Artoisenet based on work by Artoisenet, Campbell, Lansberg, Maltoni, Tramontano.

Complete NLO:

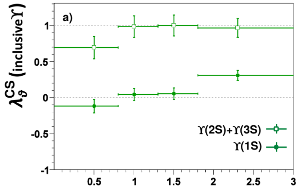
Butenschon and Kniehl (2010), Ma, Wang, and Chao (2010).



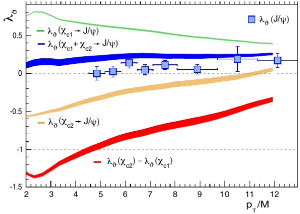
Plot from Butenschon and Kniehl (2010)

- $d\sigma/d\cos\theta \propto 1 + \alpha\cos^2\theta$
  - $\alpha = 1$ – transverse
  - $\alpha = -1$ – longitudinal
- The J/ψ polarization is **sensitive to elementary J/ψ production processes** and is a **nontrivial test to the NRQCD**.
- **NLO corrections are significant** (Butenschoen and Kneihl, 2013)
- **Polarization puzzle**: observed J/ψ are unpolarized.
- Polarization of χ_{cJ} states has not been measured yet!
- χ_{cJ} contributions might be a key to solve the polarization puzzle.

Feed-down contributions may play significant role in the polarization puzzle!



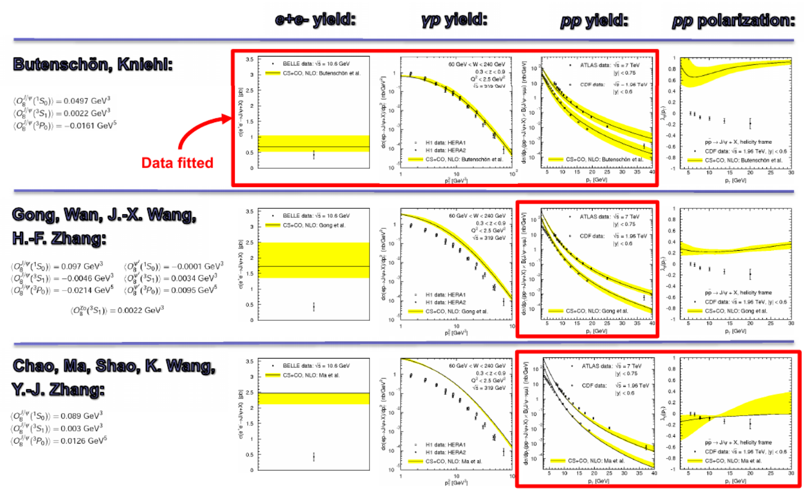
E866 data on Υ polarization.
Figure from Mod.Phys.Lett. A27 (2012) 1230022



Faccioli et al, EPJC 78, 268 (2018)

NLO NRQCD fits

Slide borrowed from M. Butenschon DIS 2016 (DESY Hamburg)

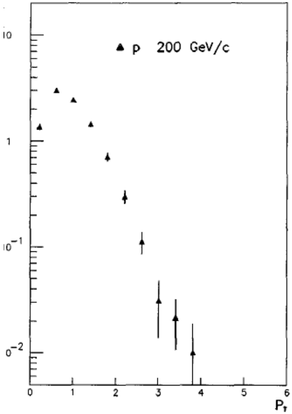


Details in Mod.Phys.Lett.A,Vol.28,No.9(2013) 1350027.
No SDML set can described all e^+e^-, γp, pp and pp polarization data.

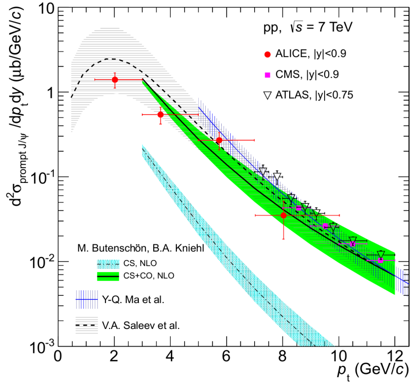
The SPD p_T range below 3-4 GeV is very complicated for the analysis:

- Collinear factorization is not applicable below 4 GeV (or even higher values) and the p_T spectrum diverges for $p_T \to 0$.
- k_T of hadrons must be taken into account.
- Parton reggeization approach (PRA, Kniehl, Vasin, Saleev, 2006) is expected to work in the SPD p_T range. See the dedicated previous talk.
- k_T-factorization approach of Baranov, Lipatov, Zotov (EPJC 75, 455 (2015), PRD 93,094012 (2016), ...) may be also applicable.
- In the k_T factorization approaches partons become massive, which notable affects polarization of charmonia states.

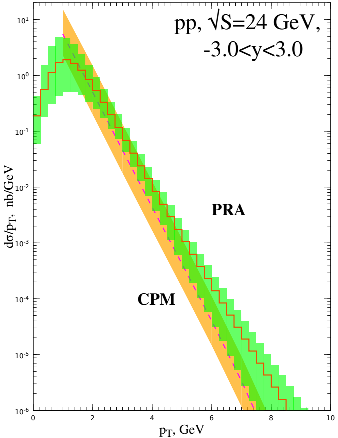
The J/ψ p_T distribution from NA3 at $\sqrt{s} = 19.4$ GeV



PRA: $d\sigma/dp_T$



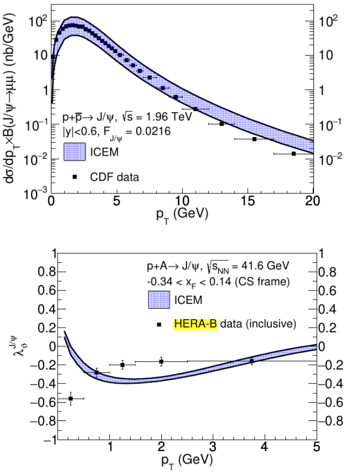
ALICE Collaboration, JHEP 1211 (2012) 065



CPM is NLO CPM calculations by B.A. Kniehl and M. Butenschoen, **PRA** is LO Parton Reggeization Approache by M.Nefedov and V. Saleev

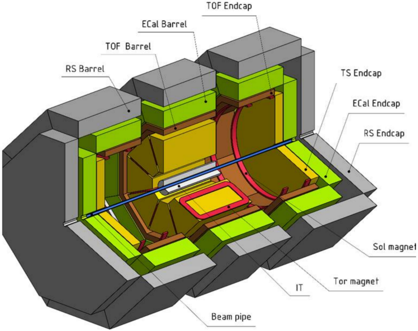
Improved CEM (ICEM, Phys.Rev.D 94, 114029 (2016), Phys.Rev. D98 114029 (2018)):

- PRA,
- $c\bar{c}$ pair must be produced with invariant mass above the mass of charmonia state and below open charm threshold,
- hadronization does not change angular momentum of $c\bar{c}$ pair.



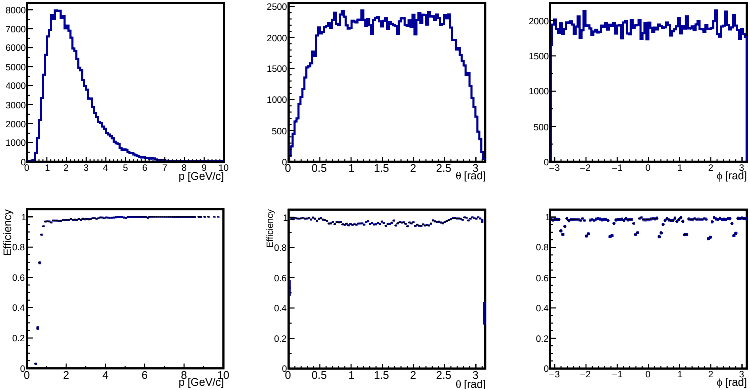
Phys.Rev. D98 114029 (2018)

MC simulations at SPD



SPD:

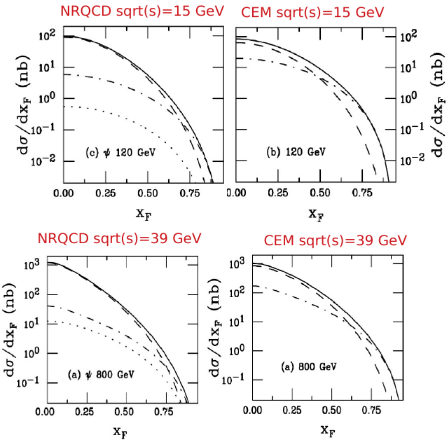
- 20M J/ψ are expected to be produced yearly,
- good momentum resolution,
- open geometry and almost 4π coverage.

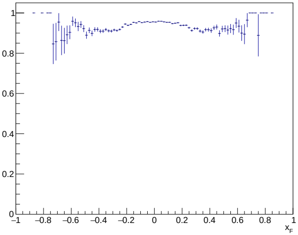


- Pythia6 $gg \to J/\psi X$
- 93% of muons reach range system

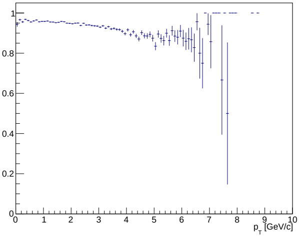
SPD: J/ψ acceptance

Phys.Rev.C61:035203,2000

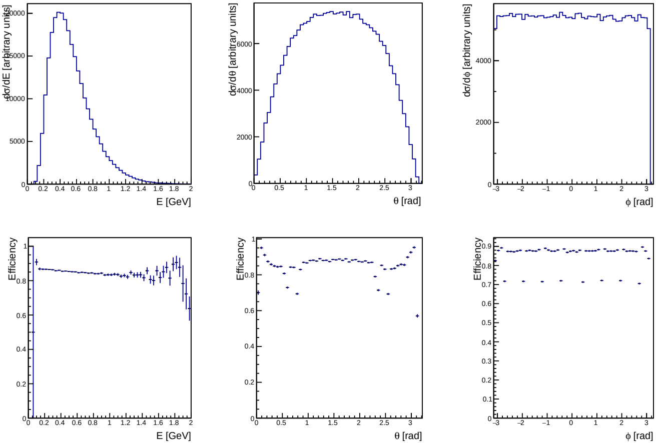




Efficiency as a function of x_F

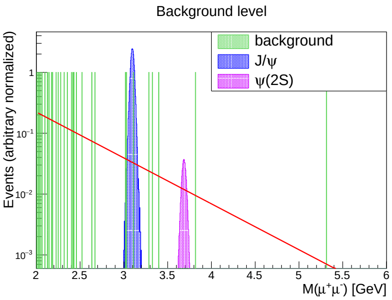


Efficiency as a function of p_T

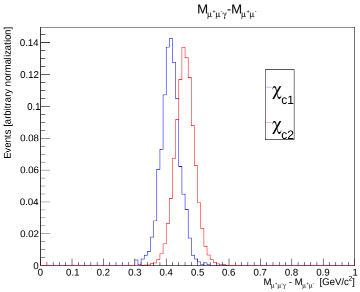


- Kinematic distributions and efficiencies for photon for $gg \to \chi_{c1}$, $\chi_{c1} \to \gamma J/\psi$.
- The total acceptance (muons reach RS and photon reaches ECAL) for $\chi_{cJ} \to \gamma J/\psi$ is about 80%.

SPD: generator level studies



- 1% momentum resolution for muons (the J/ψ peak width is $\approx$ 20 MeV)
- Background: $\pi^{\pm}$ and $K^{\pm}$ decays from 100M minimum bias events generated with Pythia6. Decays from $r < 75$ cm and $|z| < 100$ cm volume.
- Basic cuts (distance to the beam axis < 2 mm, distance between muon tracks < 1 cm, $|\cos(\theta)| < 0.9$.



- 1% momentum resolution for muons
- $5\%/\sqrt{E}$ and 0.01 rad. for photons
- the distance between peaks is comparable to the width

Summary

- Charmonia production is a powerful probe to study hadron structure. It is sensitive gluon PDF and is complimentary to Drell-Yan and prompt photon studies. For polarized beams it can be used to probe Sivers effect for gluons and may provide information on quark TMD PDFs.
- SPD is expected to provide precise measurements of TSSA in J/ψ production.
- SPD is expected to be capable to perform precise and systematic measurements of J/ψ, ψ' and possibly χ_{c1} and χ_{c2} production providing a new and significant input for validation of different theoretical approaches. This would be necessary to interpret results on spin asymmetries.
- The SPD energy region is difficult for the theoretical description. The Parton Reggeization Approach at k_T factorization approaches seem to be the most adequate for the p_T below 3-4 GeV.

Thank you!

NRQRD: explicit formulas for $\hat{\sigma}(ij \to H)$ for J/ψ and ψ'

Phys.Rev.D54:2005,1996

Example: parton scattering explicit formulas for J/ψ and ψ' ($\alpha_s^2 v^7$ and $\alpha_s^3 v^3$)

$$
\begin{aligned}
\hat{\sigma}(gg \to \psi') &= \frac{5\pi^3\alpha_s^2}{12(2m_c)^3 s}\,\delta(x_1x_2 - 4m_c^2/s)\left[\langle\mathcal{O}_8^{\psi'}({}^1S_0)\rangle + \frac{3}{m_c^2}\langle\mathcal{O}_8^{\psi'}({}^3P_0)\rangle + \frac{4}{5m_c^2}\langle\mathcal{O}_8^{\psi'}({}^3P_2)\rangle\right] \\
&\quad + \frac{20\pi^2\alpha_s^3}{81(2m_c)^5}\,\Theta(x_1x_2 - 4m_c^2/s)\,\langle\mathcal{O}_1^{\psi'}({}^3S_1)\rangle\, z^2\left[\frac{1-z^2+2z\ln z}{(1-z)^2} + \frac{1-z^2-2z\ln z}{(1+z)^3}\right] \\
\hat{\sigma}(gq \to \psi') &= 0 \\
\hat{\sigma}(q\bar{q} \to \psi') &= \frac{16\pi^3\alpha_s^2}{27(2m_c)^3 s}\,\delta(x_1x_2 - 4m_c^2/s)\,\langle\mathcal{O}_8^{\psi'}({}^3S_1)\rangle
\end{aligned}
$$

where $z(x_1, x_2) = (2m_c)^2/(sx_1x_2)$.

- 6 LDME for the direct ψ production.
- The singlet LDME ($\langle O_1({}^3S_1)\rangle$) is determined from charmonium decays or charmonium wave function in potential models.
- The $\langle O_8({}^3S_1)\rangle$ LDME is extracted from large p_t Tevatron data.
- $\Delta_8 = \left[\langle O_8^{\psi'}({}^1S_0)\rangle + \frac{3}{m_c^2}\langle O_8^{\psi'}({}^3P_0)\rangle + \frac{4}{5m_c^2}\langle O_8^{\psi'}({}^3P_2)\rangle\right]$ is extracted from fit to data of fixed-target energies.

NRQCD: on $\hat{\sigma}(ij \to H)$ for χ_{cJ}

Phys.Rev.D54:2005,1996

- Similar expressions can be written for χ_{cJ} production.
- χ_{c1} has an extra qg contribution.
- Due to heavy quark spin symmetry (holds up to $O(v^2)$) production of all χ_{cJ} states can be written as a function of two matrix elements $\langle O_1^{\chi_{c0}}(^3P_0)\rangle$ and $\langle O_8^{\chi_{c0}}(^3S_1)\rangle$.

$$\langle \mathcal{O}_1^{\chi_{cJ}}(^3P_J)\rangle = (2J+1)\,\langle \mathcal{O}_1^{\chi_{c0}}(^3P_0)\rangle$$
$$\langle \mathcal{O}_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1)\,\langle \mathcal{O}_1^{\chi_{c0}}(^3S_1)\rangle$$

- The singlet ME is determined from potential models wave functions.
- The octet ME is extracted from Tevatron data ($\langle O_8^{\chi_{c1}}(^3S_1)\rangle = 9.8 \pm 1.3$ GeV^3).